Influence of Computer-Assisted Stroke Order Learning on Chinese Character Writing in Second Language Learners

Hui SUN[a], Tianlin WANG[b] & Miao YU[a]

[a]Key Research Base of Humanities and Social Sciences of the Ministry of Education, Academy of Psychology and Behavior, Faculty of Psychology, Tianjin Normal University, 393 Binshui West Road, Xiqing District, Tianjin, China

[b]Educational & Counseling Psychology, University at Albany, State University of New York, New York, United States of America

Corresponding author: Miao Yu (E-mail: ym@tjnu.edu.cn)

Abstract

Whether stroke order learning facilitates Chinese character writing for Chinese as a Second Language (CSL) learners is a subject of debate both in teaching practice and empirical research. This study employs a self-developed computer-assisted stroke order learning system to explore the effect of stroke order learning on CSL learners' Chinese character writing by comparing their performance across different stroke order conditions (correct stroke order, random stroke order, and no stroke order) and with characters of different numbers of strokes. The results show that under the correct stroke order condition, CSL learners have a higher rate of correct output in writing characters, especially for characters with fewer strokes. Additionally, there is a trend indicating that correct stroke order may contribute to reducing writing time. The study demonstrates that learning correct stroke order helps CSL learners to write Chinese characters more accurately and possibly also more quickly; the impact of stroke order on "writing correctly" is greater than on "writing quickly." Based on empirical findings, this paper advocates for the significance and enhancement of stroke order instruction in teaching Chinese character writing.

Keywords: Stroke order learning, computer-assisted stroke order learning system, Chinese character writing, number of strokes, CSL learners

1. Introduction

As a "square script," Chinese characters are significantly different from alphabetic scripts, with complexities in line variations, writing directions, combination forms, and transition methods that are far more intricate than those of alphabetic scripts. This makes learning Chinese characters very difficult for CSL learners (Everson, 1998; Li, 2023; Shen, 2004). Among the four skills required to learn Chinese characters—listening, speaking, reading, and writing—writing is the most challenging, with CSL learners devote considerable time to writing characters but may achieve limited progress (Allen, 2008).

This complex Chinese character system is built upon a set of limited stroke order rules. There are six basic stroke order rules, namely "top before bottom," "left before right," "horizontal before vertical," "left diagonal before right diagonal," "center before sides," and "inside before closing" (Law et al., 1998). The standard stroke order for commonly used modern Chinese characters is explicitly defined in the *Stroke Orders of The Commonly Used Standard Chinese Characters* (State Language Commission, 2020). Learning stroke order is considered an essential knowledge and taught in elementary education in China. However, whether it is necessary for CSL learners to invest time and effort in learning stroke order is a contentious issue for both Chinese teachers and students (for a review, see Zhang, 2014), and existing empirical research results are still inconclusive. Although some studies have confirmed the importance of stroke order (Tsai et al., 2012; Xu & Jiang, 2020), others argue that stroke order has no effect on writing Chinese characters (Hsiaung et al., 2017; Xu et al., 2013) or may even be obstructive (Zhu et al., 2012). Therefore, this paper aims to use a computer-assisted stroke order learning system to explore the role and mechanism of stroke order learning in CSL learners' Chinese character writing and to provide empirical evidence for the necessity of stroke order instruction in language teaching.

2. Literature review

2.1. The necessity of writing Chinese characters

The complexity of Chinese character shapes leads to inefficiency in writing for second language (L2) learners, causing some scholars to consider writing a waste of time because it takes time away from developing other skills (Allen, 2008). However, some studies have found that handwriting is indeed associated with improved Chinese children's reading skills (e.g., Chan et al.,

2006; Tan et al., 2005; Tan et al., 2013). Additionally, handwriting significantly aids CSL learners in memorizing Chinese orthography and forming form-meaning mappings (e.g., Cao et al., 2013; Guan et al., 2011; Guan et al., 2015; Lyu et al., 2021). Despite the common use of pinyin for inputting Chinese characters on electronic devices, various exams, including Chinese proficiency tests such as HSK and Cambridge IGCSE–Mandarin Chinese, still require handwritten Chinese characters. In addition, spelling proficiency has been proven to contribute to text writing, as it provides more cognitive resources for higher-order cognitive processes such as organization and reflection (Yeung et al., 2013). In summary, existing evidence suggests that handwriting plays a positive role in helping CSL learners learn the orthography and semantics of Chinese characters, and is a necessary skill for taking written exams. It is therefore worthwhile to consider how to effectively promote handwriting skills among CSL learners.

In traditional L2 classrooms, teachers often guide writing through rote writing, instructing students to mechanically copy examples from textbooks (Zhang, 2014). However, rote learning without mastering correct stroke order may not achieve the desired effect. As evidenced by the investigations conducted by Deng and Hu (2022) and Tsai et al. (2012), Chinese as a Foreign Language (CFL) learners commonly make mistakes such as stroke omissions, additions, and transformations due to stroke order errors when writing Chinese characters. Examples include writing "可" as "司" without a horizontal stroke in the middle, or incorrectly representing the component to the left of the character "那" as "月." Investigations regarding stroke errors by Chinese-speaking children also show that incorrect stroke order is the main cause of writing errors, and incorrect stroke order is closely related to poorer and slower handwriting (Kong et al., 2019; Law et al., 1998). Perhaps as a further illustration of the difficulties involved in learning how to write characters, some researchers even found that CSL learners still make character formation errors during the simple task of on-sight copying, and the more stroke order errors they make, the more copying errors occur (Xu & Jiang, 2022; Tsai et al., 2012). Thus, it is evident that stroke order errors often lead to incorrect character writing among CSL learners: if CSL learners aim to accurately master handwriting skills, stroke order instruction may be beneficial, as stroke order errors can lead to handwriting mistakes.

2.2. The impact of stroke order on writing

Empirical studies directly examining the effect of stroke order learning on the writing of Chinese as a second language are scarce, and their results remain contentious. Tsai et al. (2012) used a computer-assisted program to teach stroke order to English-speaking university students. After learning, participants were asked to write the studied Chinese characters based on pinyin and meaning prompts (i.e., dictation). The results showed that compared to the prevailing workbook method used to learn characters, stroke order animation teaching significantly improved the accuracy of Chinese character writing and awareness of conventional character formation among beginners of CSL. However, Tsai et al. (2012)'s study lacked a direct comparison between the no-stroke order condition and the stroke order learning condition, making it unclear whether the effect of stroke order animation learning was due to the facilitative effect of the correct stroke order or the multimedia animation. Xu and Jiang (2022) explored the correlation between stroke order accuracy and Chinese character writing speed during the copying process by CSL learners. They found a significant positive correlation between stroke order accuracy and writing speed; the higher the stroke order accuracy, the faster the character writing speed. However, whether there is a causal relationship between stroke order and writing speed remains unclear. The role of stroke order in the writing of Chinese elementary school students has also been verified. Studies have found that knowledge of stroke order significantly contributed to writing Chinese characters correctly (Lam & McBride, 2018; Lo et al., 2016; Yeung et al., 2013), correct stroke order facilitates the cognitive processing of learners and aids in accurate writing, while wrong stroke orders lead to slower writing and more errors (Kong et al., 2019; Law et al., 1998).

However, the facilitating effect of stroke order on Chinese character writing is not universally supported by all studies. For instance, Xu et al. (2013) investigated the effects of reading (i.e., static character), animation, and writing conditions on CFL learners reproducing characters from memory. The results showed that compared to viewing static characters, watching stroke order animation did not improve the accuracy of CFL learners' writing production. However, Xu et al. (2013)'s stroke order animation was not presented within the complete frame of a character, meaning it only displayed how a character is formed stroke by stroke without presenting the complete character form. This method of presentation might hinder learners from forming a complete mental representation for the form of Chinese characters (see Nakamura et al., 2012). Moreover, the animation of a character was played for only 5 seconds, which may be too fast for beginner CSL learners who had only received 20 weeks of Chinese instruction to process properly.

Similarly, Hsiaung et al. (2017) used a stroke order teaching system, dividing learners into a stroke-order learning group (presenting stroke order animations) and a non-stroke-order learning group (presenting static characters). The study did not find a significant effect of learning stroke order animation on the correctness of Chinese character writing. However, the study did find an interaction between stroke order learning and handwriting exercises: in the group that learned stroke order, the writing accuracy of Chinese characters after handwriting practice was significantly higher than that of characters without practice. In contrast, in the group that did not learn stroke order, practicing handwriting did not significantly affect the writing accuracy. These results point to the possibility that writing practice conducted with the correct stroke order is effective. In addition, this study did not control for the familiarity of the characters, which could easily confound learning outcomes given students' varied prior knowledge.

Some researchers argue that stroke order animations may have a negative effect on learners' Chinese character writing. Zhu and Hong (2005) examined the impact of voiced-pronunciation and stroke order animation on production of characters by CFL learners. Their findings indicated that the writing performance of those who learned both pronunciation and animations was significantly inferior to that of learners who only learned pronunciation, thereby demonstrating a hindering effect of stroke order animations on the writing of Chinese characters. In a subsequent study, Zhu et al. (2012) also found a negative impact of stroke order animations on written production of Chinese characters, suggesting that the negative effects of stroke order animations are due to the split attention effect caused by simultaneously inputting animation and pronunciation information. Studies on Chinese children also found that restricting children to learn to write (draw shapes) according to the correct stroke order may have a detrimental effect on subsequent recognition, as restricting learners to write according to the correct stroke order increases their cognitive load (Merritt et al., 2020). Thus, there still exists considerable disagreement regarding whether stroke order promotes Chinese character writing.

As previously mentioned, the complex visual properties of Chinese characters pose a great challenge to CSL learners' writing. This challenge is closely related to the learners' strategies for processing characters. Past research has found that CSL learners exhibit a significant stroke number effect when performing character judgment tasks, indicating that they tend to use an analytical strategy in processing characters (Jiang et al., 2020; Jiang & Feng, 2022). This strategy makes it more difficult for learners to process and remember complex characters with many strokes

compared to those with fewer strokes (Chang et al., 2016). Previous studies suggest that stroke order information helps to decode characters by using the spatial relationships of strokes (Giovanni, 1994; Yin & Zhang, 2020). Therefore, it can be speculated that stroke order might assist CSL learners in analytically processing characters, thereby facilitating their memory and writing, with potentially greater effects on characters with more strokes. However, the high complexity of characters with many strokes can increase learners' processing load (Tseng & Chow, 2000; Kong, 2019), which may occupy cognitive resources for learning stroke order, thus diminish the effects of stroke order. Unfortunately, previous empirical studies on the effect of stroke order on character processing have not considered the impact of the number of character strokes on the effect of stroke order. Therefore, it is necessary to use characters with different numbers of strokes to further explore the impact of stroke order on CSL learners' writing of characters with varying stroke numbers.

In addition, past studies using stroke order animations only compared the presentation of stroke order animations and static characters (e.g., Hsiaung et al., 2017; Xu et al., 2013). Xu et al. (2020) showed that stroke order animations and static characters are influenced by different sensory systems, such that presenting static characters only involves the visual process, while stroke order animations involve both visual processing and the motor decoding system, which also significantly affects character processing (Nakamura et al., 2012; Schubert et al., 2018; Yin & Zhang, 2020). Therefore, past studies that only used stroke order animations and static characters cannot parse out the potential confounding variable introduced by the dynamic information of stroke order animations. In the present study, we added a random stroke order condition to rule out the impact of motor system processing on the results.

2.3. Research Questions

In summary, there is no consensus on the role of stroke order in Chinese character handwriting. While some studies support the facilitative role of stroke order and found that correct stroke order helps learners memorize the correct orthographical form of characters, conserving cognitive resources for fast and exact reproduction of characters (Giovanni, 1994; Tsai et al., 2012; Xu & Jiang, 2020), other studies have indicated that stroke order does not aid in character writing (Hsiaung et al., 2017; Xu et al., 2013). Some researchers further argue that learning stroke order animations may distract learners' attention (Zhu et al., 2012) or increase their cognitive load

(Merritt et al., 2020), thus hindering character writing. Therefore, based on the controversies and limitations of past research, we aimed to answer the following research questions:

1. Does learning stroke order facilitate CSL learners in writing Chinese characters correctly and quickly?
2. Is the effect of learning stroke order moderated by the number of strokes in Chinese characters?

To address the first question, we will compare the effects of different learning conditions (correct stroke order, random stroke order, and no stroke order) on the accuracy and time taken to write Chinese characters. For the second question, we will examine the differences and interactions in accuracy and time for writing Chinese characters with varying stroke numbers across different learning conditions.

Chinese characters, as a logographic script, pose challenges for learners who spell based on phonetic cues (Jiang et al., 2018; McBride, 2015). Therefore, establishing a solid and precise mental representation of the character's form is key to reproducing the correct written form from memory (Wong & Zhou, 2022). Past research supports the notion that stroke order information is stored in memory, forming a motor program that serves as an effective cue for retrieving character representations from memory (Giovanni, 1994; Guan et al., 2015; Nakamura et al., 2012; Qiu & Zhou, 2010; Yin & Zhang, 2020; Yu et al., 2011). Therefore, this study hypothesizes that learning the correct stroke order helps learners retrieve the correct orthographic representations from memory, thus improving the accuracy of CSL learners' written reproduction of Chinese characters and shortening writing time. Based on the characteristics of Chinese characters, this study further hypothesizes that the effect of stroke order learning on writing will be moderated by the number of strokes in the characters.

3. Method

3.1. Participants

Forty-three CSL learners participated in the experiment (16 males). All participants were from a university in North China, with an average age of 22.7 years (*SD* = 3.47). Power analysis conducted using G*Power 3.1.9.7 software (Faul et al., 2007) indicated that, with a significance

level of $\alpha = .05$ and a medium effect size ($f = .25$), the sample size achieved a statistical power of .99.

The participants' native languages were: Thai (12), English (8), Vietnamese (6), Urdu (3), French (2), Spanish (2), Russian (2), and other languages (8)—including Swahili, Kikuyu, Arabic, Kikongo, Mongolian, Lao, Malay, and Igbo (1 each). At the time of the experiment, 10 students had passed HSK level 4, 24 had passed HSK level 5, and 9 had passed HSK level 6.

All participants had normal or corrected-to-normal vision, were right-handed, and had no writing or learning disabilities. The study was approved by the university's Institutional Review Board, and each participant received 60 yuan as reward after the experiment.

3.2. Experimental design

The study adopted a 3 (stroke order learning condition: correct stroke order, random stroke order, no stroke order) × 2 (number of strokes: fewer strokes, more strokes) within-subjects design. The dependent variables were the accuracy and time of Chinese character writing.

3.3. Materials

Eighteen unfamiliar low-frequency compound simplified characters (including left-right structure, top-bottom structure, and enclosed structure) were selected as learning materials, covering the 6 main stroke order rules (Law et al., 1998). The characters were divided into two groups based on the number of strokes, with 9 characters each. The characters in the fewer-strokes group had 5-7 strokes (Mean = 6); the more-strokes group had 10-12 strokes (Mean = 11). The English translation frequency of the fewer-strokes characters (Mean = 7256 occurrences/million, SD = 7481) and the more-strokes characters (Mean = 4828 occurrences/million, SD = 4200) from the British National Corpus (https://www.english-corpora.org/bnc/) did not significantly differ, $t(16) = .849$, $p = .187$, Cohen's $d = .42$.

The three learning conditions—correct stroke order, random stroke order, and no stroke order—each included 6 characters. The number of strokes and spatial structure types of the characters in the three conditions were identical, and the differences in English translation frequency were not significant, $F(2, 17) = .07$, $p = .933$, $\eta^2 = .01$.

To ensure that the target characters were unfamiliar to the participants, a naming test was conducted with 30 native Chinese-speaking university students, none of whom could correctly name the selected characters.

3.4. Experimental apparatus

The study used a self-developed computer-assisted stroke order learning system as a stroke order teaching tool. Figure 1 shows interface examples for the three stroke order learning conditions. The target character is displayed in the upper left corner, with its English translation on the right, the pinyin of the character at the bottom left, while the system automatically sounds the pronunciation of the character. Stroke order animations are shown at the bottom right.

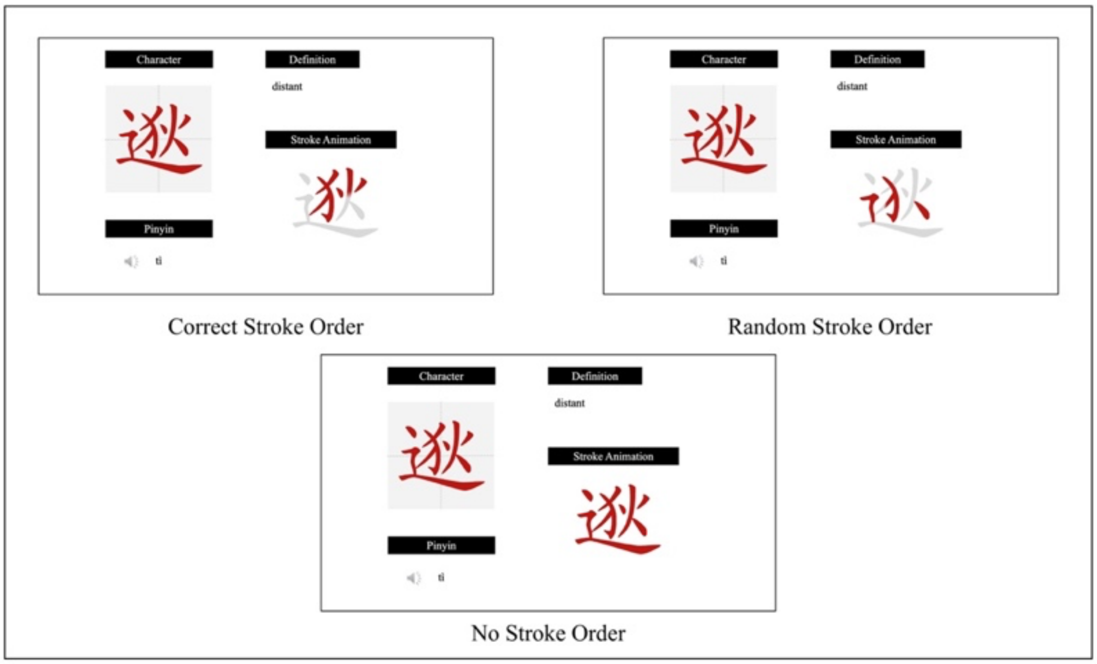

Figure 1. Example of the character learning interface.

3.5. Experimental procedure

The study consisted of two phases: a learning phase and a test phase.

3.5.1 Learning phase

Before formal learning began, the experimenter introduced the stroke order learning system to the participants and demonstrated examples to aid their understanding. Once the participants are fully acquainted with the system, the formal learning started. Initially, a fixation point was presented for 800ms. Subsequently, the Chinese character learning interface (see Figure 1) appeared, displaying a static character, its pinyin, and the English translation of the character, while the system automatically sounded the character's pronunciation. Four seconds later, for the correct

stroke order animation and random stroke order animation conditions, the animation was displayed; for the no stroke order condition, a static character was presented.

The presentation method for the stroke order animation is shown in Figure 2. A grey character first appeared for 4 seconds, followed by the first stroke animation, with each stroke lasting 1000ms (during which the stroke was played at a uniform speed), and after each stroke, there was a 500ms interval before the next stroke appeared. In the correct stroke order condition, the animation was played according to the correct sequence (State Language Commission, 2020), while in the random stroke order condition, the strokes were presented in a random sequence and direction. In the no stroke order condition, a static character was presented.

All characters were presented in a pseudorandom manner, specifically, we combined the three learning conditions in different orders to form six sequence lists. Each participant was randomly assigned to one of these sequence lists for their learning. Each character's animation and pronunciation were played three times. The learning time for each character was equal across the different conditions, and the entire learning process lasted about 45 minutes.

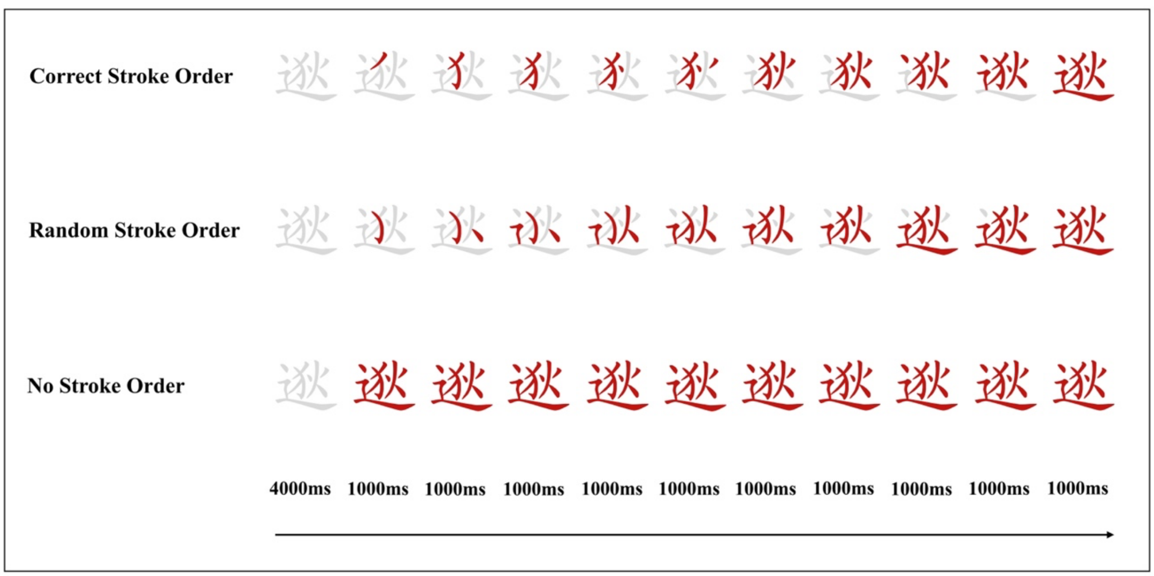

Figure 2. An illustration of the stroke order animations in three learning conditions.

3.5.2. Test phase

A writing test (i.e., dictation) was carried out with stimuli presented using E-prime 2.0. Before the test onset, 1-2 characters were provided as practice material to familiarize participants with writing on a digital screen. During testing, the target character's pinyin and English translation

were displayed on the monitor, and the character's pronunciation was sounded. Participants were instructed to write the corresponding character to match the prompts on the display. A Wacom digital screen and stylus were used to record the trajectory of the participants' writing for subsequent data analysis. Based on previous studies (Hsiaung et al., 2017; Xu et al., 2013) and the purpose of this study, the accuracy of the character writing task included two scoring criteria:

(1) Loose criterion accuracy: Scored based on the proportion of strokes written correctly by the participant relative to the total number of strokes in the character. For example, for the target character "逖," if the learner wrote 3 strokes correctly, the score would be 3/10. The range of scores was 0-1 (including 0 and 1) using this criterion.

(2) Strict criterion accuracy: All strokes and their positions must be written correctly to score. Using "逖" as an example, the learner would only receive 1 point if all strokes and their positions are written correctly; otherwise, the score would be 0. Under this criterion, participants can only score either 0 or 1.

The loose scoring criterion was used to assess the learners' mastery of each character and its individual strokes, while the strict criterion was used to measure the learners' ability to write the entire character exactly. Three graduate students, native in Chinese, independently scored the accuracy of the characters written by the learners. If there was a discrepancy, the characters were re-evaluated until a consensus was reached among the scorers. Writing time was defined as the duration from the appearance of the semantic and phonetic prompts to the completion of writing by the participant.

4. Results

A total of 42 valid datasets were collected. Only data where the participant's writing score was not zero were included in the writing time analysis. Additionally, the writing time data were log-transformed before the analysis.

Using the R environment (R Core Team, 2020) and the lme4 package (Bates et al., 2018), Linear Mixed Models (LMMs) were employed for analyzing the accuracy scores based on the loose criterion and the writing time data, while Generalized Linear Mixed Models (GLMMs) were used for analyzing the accuracy scores based on the strict criterion, as these scores were binomial. Compared to traditional ANOVA, (G)LMMs incorporate all raw data into the model, resulting in higher data utilization. In the analysis, the maximal random-effect structure is used, incorporating

both participants and items into the model (Baayen et al., 2008), which makes the calculation results easier to interpret. Participants and items were considered as crossed random factors, with learning conditions and character stroke numbers as fixed factors in the model. The random intercepts and slopes for participants and items were also considered. All analyses started with the maximal random effects model (Barr et al., 2013); if the maximal model with random effects could not be successfully fitted, the model was simplified by first removing the correlations for items, then the slopes for items, and if it still could not be fitted, the correlations and slopes for participants were removed in sequence until a successful fit was obtained. The lmerTest package (Kuznetsova et al., 2020) was used to calculate *p*-values for fixed effects. After significant interactions, the Emmeans package (Lenth, 2022) in the R environment was used to compute simple effects between primary conditions.

The mean accuracy rates for writing characters with different numbers of strokes under different learning conditions are shown in Table 1, and the writing time are shown in Table 2.

Table 1 Average writing accuracy rates (standard deviation) under different conditions.

	Loose criterion		Strict criterion	
	More strokes	Fewer strokes	More strokes	Fewer strokes
Correct stroke order	.62 (.43)	.73 (.40)	.45 (.50)	.63 (.48)
No stroke order	.52 (.42)	.36 (.43)	.22 (.41)	.18 (.39)
Random stroke order	.44 (.44)	.49 (.43)	.20 (.40)	.30 (.46)

Table 2 Average writing time in seconds (standard deviation) under different conditions.

	More strokes	Fewer strokes
Correct stroke order	25.33 (25.11)	22.18 (16.21)
No stroke order	29.29 (3.71)	24.70 (18.61)
Random stroke order	30.60 (2.10)	25.28 (24.54)

The statistical analysis results for the loose criterion scoring (as shown in Table 3 and Figure 3) revealed a significant main effect of stroke order learning condition. The writing accuracy under the no-stroke order condition (t = -6.89, p < .001) and random stroke order condition (t = -6.07, p < .001) were both significantly lower than the correct stroke order condition, with no significant difference in writing accuracy between the random stroke order and no-stroke order conditions (t = .82, p = .41). The main effect of the number of strokes in a character was not significant (t = .14, p = .89). There was an interaction between the difference in accuracy rates of the correct and no-

stroke order conditions and the number of strokes. Further analysis of simple effects showed that for characters with fewer strokes, the accuracy rate under the no-stroke order condition was significantly lower than under the correct stroke order condition (t = -7.68, p <.001). However, for characters with more strokes, there was no significant difference in the accuracy rate between the correct and no-stroke order conditions (t = -2.07, p = .10).

The statistical analysis results for the strict criterion scoring (as shown in Table 3 and Figure 3) indicated a significant main effect of stroke order learning condition. The writing accuracy under the no-stroke order condition (z = -7.91, p < .001) and the random stroke order condition (z = -6.83, p < .001) were significantly lower than the correct stroke order condition, with no significant difference between the random stroke order and no-stroke order conditions (z = 1.34, p = .18). The main effect of the number of strokes in a character was significant; learners had a higher writing accuracy rate for characters with fewer strokes than for those with more strokes (z = 2.27, p < .05). Similarly, the interaction between the difference in accuracy rates of the correct and no-stroke order conditions and the number of strokes was significant. Further simple effect analysis showed that for both characters with more strokes (z = 4.08, p < .001) and fewer strokes (z = 7.18, p < .001), the accuracy rate under the correct stroke order condition was significantly higher than under the no-stroke order condition. The interaction was such that the difference in accuracy rate between the correct and no-stroke order conditions was greater for characters with fewer strokes than for those with more strokes.

Table 3. Fixed effect estimates of writing accuracy under different conditions.

	Loose criterion				Strict criterion			
Fixed effect	*b*	*SE*	*t*	95%CI	*b*	*SE*	*z*	95%CI
Intercept	.53	.03	17.64***	[.47, .59]	-1.03	.19	-5.39***	[-1.40, -.66]
Stroke order learning								
N vs C	-.24	.03	-6.89***	[-.31, -.17]	-1.82	.23	-7.91***	[-2.27, -1.37]
R vs C	-.21	.03	-6.07***	[-.28, -.14]	-1.50	.22	-6.83***	[-1.94, -1.07]
R vs N	.03	.03	.82	[-.04, .10]	.32	.24	1.34	[-.15, .78]
Stroke number								
FS vs MS	.004	.03	.14	[-.05, .06]	.42	.18	2.27*	[.06, .78]
Interaction								
Stroke number × N vs C	-.27	.07	-3.96***	[-.41, -.14]	-1.11	.45	-2.47*	[-1.98, -.23]

Note: *p < .05, **p < .01, ***p < .001. C = Correct Stroke Order, N = No Stroke Order, R = Random Stroke Order; FS = Fewer strokes, MS = More strokes.

Table 4. Fixed effect estimates of writing time under different conditions.

Fixed effect	*b*	*SE*	*t*	95%CI
Intercept	9.95	.05	188.18***	[9.85, 1.05]
Stroke order learning				
N vs C	.12	.07	1.71	[-.02, .25]

R vs C	.18	.07	2.64**	[.05, .31]
R vs N	.06	.07	.84	[-.08, .20]
Stroke number				
FS vs MS	-.18	.06	-3.17**	[-.29, -.07]
Interaction				
Stroke number × N vs C	-.06	.14	.65	[-.33, .20]

For the writing time metric (as shown in Table 4), statistical analysis results indicated a significant main effect of stroke order learning condition. Writing time for both the no-stroke order (marginally significant: $t = 1.71$, $p = .089$) and random stroke order ($t = 2.64$, $p = .009$) conditions were greater than for the correct stroke order condition, with no significant difference in writing time between the random stroke order and no-stroke order conditions ($t = .84$, $p > .05$). There was a significant main effect of the number of strokes in characters, with writing time for characters with fewer strokes being significantly less than for characters with more strokes ($t = -3.17$, $p = .002$). The interaction between the differences in writing time for correct stroke order, no-stroke order, and correct stroke order, random stroke order with the number of character strokes was not significant ($|t|\text{s} < 1.07$, $p\text{s} > .29$). The statistical results for writing time suggest that the correct stroke order condition helps learners increase writing speed.

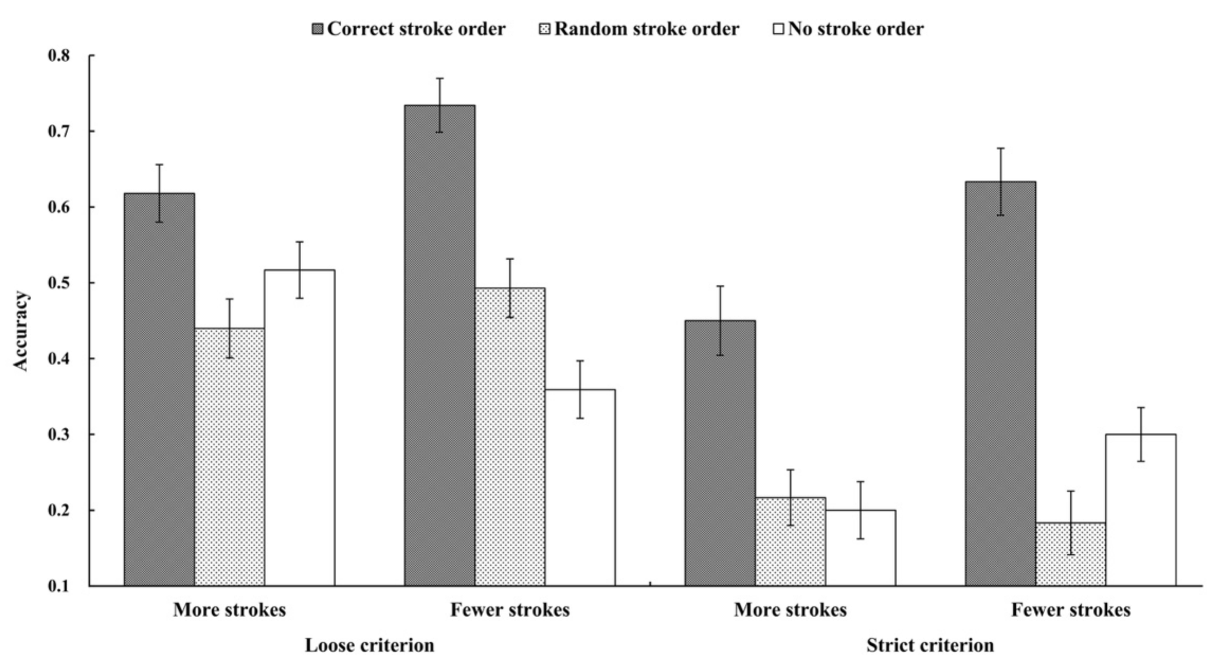

Figure 3. Writing accuracy rates under the loose criteria (left) and strict criteria (right). Error bars depict +/- standard error.

5. Discussion

Using a self-developed computer-assisted stroke order teaching system, this study examined the impact of different stroke order presentations on CSL learners' writing of Chinese characters with varying numbers of strokes. The results indicated that, under both strict (where all strokes must be correct to score) and loose (where scores are proportional to the number of correctly written strokes) criteria, writing accuracy in the correct stroke order condition was significantly greater than in both the no stroke order and random stroke order conditions. Moreover, compared to characters with more strokes, stroke order learning was more effective for correctly writing characters with fewer strokes. In terms of writing time, the results also suggested that learning the correct stroke order helped to some extent in increasing writing speed. The findings of this study suggest that learning the correct stroke order helps CSL learners understand and memorize the orthography of Chinese characters, allowing them to write the characters both correctly and possibly more quickly.

The results of this study are consistent with previous research on CSL beginners (Tsai et al., 2012; Xu & Jiang, 2020) and Chinese children (Lam & McBride, 2018; Lo et al., 2016; Yeung et al., 2013), all of which have demonstrated the facilitative role of correct stroke order in writing Chinese characters. This study further extends this conclusion to a group of intermediate-level Chinese learners.

The advantage of correct stroke order in writing can be explained by the central-peripheral cognitive processes theory of writing. The central cognitive processes of writing involve retrieving the appropriate lexicon (Chinese characters) and their correct written forms and preserving them in memory. The peripheral processes are responsible for converting the mental representation of characters from memory into motor programs, further organizing the writing movement (Kandel & Perret, 2015; Li et al., 2022; Yang et al., 2019). From the perspective of the central cognitive processes of writing, the dynamic encoding of the correct stroke order condition draws the learner's attention to the spatial direction and sequence of strokes, providing more visual information for memory retention of characters. This helps learners conduct a fine-grained visual orthographic analysis of the characters, further establishing a more solid and precise memory representation of the character form (Chang et al., 2014; Guan et al., 2011). In the present study, we found that the facilitative effect of correct stroke order under strict criterion scoring is greater than under the loose criterion, further suggesting that learning the correct stroke order not only helps learners

retrieve the character form representations they are about to produce but also aids in the reproduction of an exact written form from memory. Peripheral executive processes require writers to pay clear attention to the spatial layout and sequence of strokes. Correct stroke order provides a systematic set of rules for controlling the position of strokes, which helps enhance the regularity of hand movements when writing Chinese characters, thereby guiding the writing. When writing a character with complex strokes, if the strokes are randomly combined, each writing instance increases the cognitive load. In contrast, writing according to the correct stroke order is a systematic writing method. This consistent movement helps form the motor program for writing characters into long-term memory (Guan et al., 2015; Lam & McBride, 2018). Once the stroke order is stored in the motor program, subsequent strokes will continue to follow, thus becoming an effective cue for retrieving characters from memory, helping to initiate the orthographic representation of the character (Giovanni, 1994), allowing learners to write the characters more automatically. Further, when the regular sequence of writing makes motor execution easier and smoother, it helps reduce the cognitive load of recalling the position and sequence of strokes during writing. By freeing up more cognitive resources to retrieve the orthographic structure of characters, it thereby helps learners to write more accurately and quickly (Lam & McBride, 2018; Xu & Jiang, 2022). The results of this study provide new insight regarding the central-peripheral process theory of Chinese character writing from the perspective of stroke order processing.

In contrast to the findings of this study, previous research using multimedia technology has suggested that presenting stroke order animations alongside the pronunciation of Chinese characters can have a negative effect on writing output due to split attention (Zhu et al., 2012) and increased cognitive load (Merritt et al., 2020). However, we found that stroke order has a facilitative effect on writing Chinese characters, which may be related to the design of the stroke order animation system used in this study. Our stroke order animation system presents the pronunciation (pinyin) and semantic information of the character 4 seconds before formally presenting the stroke order animation. Therefore, learners have ample time to process this information, which may help avoid split attention and reduce memory load, thereby enabling learners to focus on character form processing. This suggests that future stroke order teaching should be careful not to present form, sound, and meaning information simultaneously to reduce learners' cognitive load or avoid split attention effects.

Comparing stroke order animations with static characters alone does not eliminate the influence of motor system processing on orthographic processing. Therefore, this study added a random stroke order condition to eliminate potential confounds caused by motor information. We found that under the random stroke order condition, learners' correct writing rates were significantly lower than under the correct stroke order condition, and there was no significant difference between the random and no stroke order conditions. This finding better eliminates the role of movement alone in writing Chinese characters and illuminates the impact of stroke order. This result is consistent with Schubert et al. (2018)'s research on letters, further supporting that mere motor information is not sufficient to facilitate processing; correct stroke order is a necessary condition for strengthening visual orthographic representations. In our study, correct stroke order facilitated the establishment of a mental motor memory of Chinese character strokes. When learners saw a character, these memory traces were activated, providing cues for writing the character; on the contrary, presenting strokes in a random order prevented learners from establishing a corresponding motor program, hence no retrieval cues were available for subsequent writing output (Giovanni, 1994).

We further found an interaction between stroke order learning conditions and stroke numbers under both scoring criteria for accuracy rates. Specifically, the facilitative effect of correct stroke order on writing was only found for characters with fewer strokes. The effect of stroke order learning may be influenced by processing load; characters with many strokes have a higher processing load due to their complexity (Chang et al., 2016; Tseng & Chow, 2000). In our study, intermediate-level learners may not be able to learn and memorize their stroke orders in a short period of time. In contrast, for characters with fewer strokes, learners can process the characters more easily, having more cognitive resources available for processing stroke order information, thus the role of stroke order became evident. Future studies could further explore the effect of stroke order on characters with different numbers of strokes for advanced-level Chinese learners.

Our results differ from those of Hsiaung et al. (2017) and Xu et al. (2013), which did not find a facilitative effect of stroke order animations on writing. We speculate that the differences may be due to the Chinese proficiency of the participants. Participants in our study were international students in China with intermediate levels of Chinese proficiency, while Hsiaung et al. (2017) and Xu et al. (2013) used beginners lacking experience in writing Chinese characters. Previous studies recruiting learners at different levels have found an influence of participant level on the effect of

stroke order. For example, Xu and Jiang (2022) found that stroke order knowledge was significantly related to the writing performance of intermediate and advanced level learners, but not with beginners, and Kong et al. (2019) also found that stroke order knowledge significantly contributed to spelling only for third-grade children, not for first graders. Writing is a challenging skill that requires the synthesis of orthographic coding, visual-motor integration, motor planning, and execution (Guan et al., 2011; Lam & McBride, 2018; Nakamura et al., 2012; Tseng & Chow, 2000; Xu et al., 2020). For inexperienced, low-level learners, the writing task is particularly difficult and may occupy the cognitive resources needed for recalling stroke order, thereby not demonstrating the effect of stroke order. Therefore, it is plausible that stroke order skills may only be effective in learners with foundational skills with regard to Chinese characters. However, such speculation based on previous and present study results need to be investigated by future research: by comparing learners at different levels or conducting longitudinal research to further determine whether the effect of stroke order is influenced by learners' proficiency level vis-à-vis the mechanisms for such influence.

Previous empirical research on stroke order animations has primarily focused the impact of stroke order from the perspective of writing accuracy (e.g., Hsiaung et al., 2017; Tsai et al., 2012; Xu et al., 2013). This study is the first to provide empirical support for the important role of correct stroke order in writing from both the perspectives of accuracy and writing speed. However, it should be noted that while the writing speed for the correct stroke order condition was significantly faster than that for the random stroke order condition, the difference between the correct stroke order and no stroke order conditions was only marginally significant. Compared to this pattern, the facilitative effect of the correct stroke order condition on the accuracy measure was significant for both contrasts (i.e., correct order vs. no order; correct order vs. random order). This suggests that the role of stroke order is more clearly reflected in the writing outcome (writing correctly), rather than the writing process (writing quickly). The results of this study hold clear value for the practice of learning and teaching Chinese characters. Writing correctly, especially for practical purposes such as exams, is evidently more important than writing quickly.

The findings of this study suggest that stroke order teaching should be emphasized and strengthened in international Chinese education. Firstly, teachers should give importance to stroke order in their teaching, thoroughly introducing stroke order rules to students, demonstrating the method of writing Chinese characters with the correct stroke order, and encouraging students to

adhere to the correct stroke order in writing practice. Learners should also reinforce the correct writing stroke order in their daily writing practice to gradually acquire automated writing skills. Secondly, this study provides a valuable method of learning Chinese characters, namely stroke order animations. With portable devices and downloadable applications becoming increasingly common, animations offer many convenient and flexible learning opportunities. Results from this study suggest that it may be advantageous to fully utilize animated resources for learning, such as by including links to stroke order animation tutorials in Chinese textbooks. This would enable learners to learn how to write Chinese characters without spatial or time constraints.

6. Conclusion

This study employed a self-developed computer-assisted stroke order animation learning system to explore how learning stroke order affects CSL learners' ability to write Chinese characters, particularly those with varying numbers of strokes. The findings suggest that learning the correct stroke order helps CSL learners write characters more accurately, with a greater facilitative effect on writing characters with fewer strokes. Additionally, learning the correct stroke order also showed a tendency to reduce writing time. The findings indicate that mastering the correct stroke order not only enhances the accuracy of CSL learners in writing Chinese characters but also may increase their writing speed. These results highlight the importance of stroke order in teaching and learning Chinese character writing.

References

Allen, J. (2008). Why learning to write Chinese is a waste of time: A modest proposal. *Foreign Language Annals, 41*(2), 237-251. https://doi.org/10.1111/j.1944-9720.2008.tb03291.x

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*(4), 390-412. https://doi.org/10.1016/j.jml.2007.12.005

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*(3), 255-278. https://doi.org/10.1016/j.jml.2012.11.001

Bates, D., M., Maechler, M., Bolker, B., & Walker, S. (2018). Lme4: Linear mixed-effects models using 'Eigen' and S4. Version 1.1-31. https://cran.r-project.org/web/packages/lme4/index.html

Cao, F., Vu, M., Lung Chan, D. H., Lawrence, J. M., Harris, L. N., Guan, Q., Xu, Y., Perfetti, C. A. (2013). Writing affects the brain network of reading in Chinese: A functional magnetic resonance imaging study. *Human Brain Mapping*, *34*(7), 1670-1684. https://doi.org/10.1002/hbm.22017

Chan, D. W., Ho, C. S. H., Tsang, S. M., Lee, S. H., & Chung, K. K. (2006). Exploring the reading-writing connection in Chinese children with dyslexia in Hong Kong. *Reading and Writing, 19,* 543-561. http://dx.doi.org/10.1007/s11145-006-9008-z

Chang, L. Y., Plaut, D. C., & Perfetti, C. A. (2016). Visual complexity in orthographic learning: Modeling learning across writing system variations. *Scientific Studies of Reading,* 20(1), 64-85. https://doi.org/10.1080/10888438.2015.1104688

Chang, L. Y., Stafura, J. Z., Rickles, B., Chen, H. C., & Perfetti, C. A. (2014). Incremental learning of Chinese orthography: ERP indicators of animated and static stroke displays on character form and meaning acquisition. *Journal of Neurolinguistics, 33*(1), 78-95. https://doi.org/10.1016/j.jneuroling.2014.09.001

Deng, S., & Hu, W. (2022). An examination of Chinese character writing errors: Developmental differences among Chinese as a foreign language learners. *Journal of Chinese Writing Systems*, *6*(1), 39-51. https://doi.org/10.1177/25138502211066611

Everson, M. E. (1998). Word recognition among learners of Chinese as a foreign language: Investigating the relationship between naming and knowing. *The Modern Language Journal*, *82*(2), 194-204. https://doi.org/10.1111/j.1540-4781.1998.tb01192.x

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175-191. https://doi.org/10.3758/BF03193146

Giovanni, F. B. A. (1994). Order of strokes writing as a cue for retrieval in reading Chinese characters. *European Journal of Cognitive Psychology, 6*(4), 337-355. https://doi.org/10.1080/09541449408406519

Guan, C. Q., Liu, Y., Chan, D. H. L., Ye, F., & Perfetti, C. A. (2011). Writing strengthens orthography and alphabetic-coding strengthens phonology in learning to read Chinese. *Journal of Educational Psychology, 103*(3), 509-522. https://psycnet.apa.org/doi/10.1037/a0023730

Guan, C. Q., Perfetti, C. A., & Meng, W. (2015). Writing quality predicts Chinese learning. *Reading and Writing, 2*8(6), 763-795. https://doi.org/10.1007/s11145-015-9549-0

Hsiaung, H. Y., Chang, Y. L., Chen, H. C., & Sung, Y. T. (2017). Effect of stroke-order learning and handwriting exercises on recognizing and writing Chinese characters by Chinese as a foreign language learners. *Computers in Human Behavior, 74*, 303-310. https://doi.org/10.1016/j.chb.2017.04.022

Jiang, N. (2018). *Second Language Processing: An Introduction*. Routledge. https://doi.org/10.4324/9781315886336

Jiang, N., & Feng, L. (2022). Analytic visual word recognition among Chinese L2 learners. *Foreign Language Annals, 55*(2), 540–558. https://doi.org/10.1111/flan.12604

Jiang, N., Hou, F., & Jiang, X. (2020). Analytic versus holistic recognition of Chinese words among L2 Learners. *The Modern Language Journal, 104*(3), 567-580. https://doi.org/10.1111/modl.12662

Kandel, S., & Perret, C. (2015). How does the interaction between spelling and motor processes build up during writing acquisition? *Cognition*, 136, 325–336.

Kong, M. Y. (2019). The association between children's common Chinese stroke errors and spelling ability. *Reading and Writing, 33*(1), 635-670. https://doi.org/10.1007/s11145-019-09981-4

Kuznetsova, A., Brockhof, P. B., & Christensen, R. H. B. (2020). lmerTest: Tests in linear mixed effects models. Version, 3, 1–3. http://CRAN.R–project.org/package = lmerTest

Lam, S. S. Y., & McBride, C. (2018). Learning to write: The role of handwriting for Chinese spelling in kindergarten children. *Journal of Educational Psychology, 110*(7), 917-930. https://psycnet.apa.org/doi/10.1037/edu0000253

Law, N., Ki, W. W., Chung, A. L. S., Ko, P. Y., & Lam, H. C. (1998). Children's stroke sequence errors in writing Chinese characters. *Reading and Writing, 10*(3), 267-292. https://doi.org/10.1023/A:1008091730338

Lenth, R. (2022). Emmeans: Estimated marginal means, aka least squares means. Version, 1(7), 2. https://CRAN.R-project.org/package = emmeans

Li, J., Liu, Y., Wang, Y., Wang, N., Ji, Y., Wei, T., Bi, H.-Y., & Yang, Y. (2022). Functional brain networks underlying the interaction between central and peripheral processes involved in Chinese handwriting in children and adults. *Human Brain Mapping, 44*(1), 1-14. https://doi.org/10.1002/hbm.26055

Li, M. (2023). A review of technology enhanced Chinese character teaching and learning in a digital context. *Language Learning and Technology, 27*(3), 65–82.

Lo, L. Y., Yeung, P. S., Ho, C. S. H., Chan, D. W. O., & Chung, K. (2016). The role of stroke knowledge in reading and spelling in Chinese. *Journal of Research in Reading, 39*(4), 367-388. https://doi.org/10.1111/1467-9817.12058

Lyu, B., Lai, C., Lin, C. H., & Gong, Y. (2021). Comparison studies of typing and handwriting in Chinese language learning: A synthetic review. *International Journal of Educational Research*, *106*, 101740. https://doi.org/10.1016/j.ijer.2021.101740

McBride, C. A. (2015). Is Chinese Special? Four aspects of Chinese literacy acquisition that might distinguish learning Chinese from learning alphabetic orthographies. *Educational Psychology Review, 28*(3), 523-549. https://doi.org/10.1007/s10648-015-9318-2

Merritt, E., Swain, S. N., Vinci-Booher, S., & James, K. H. (2020). Constraining stroke order during manual symbol learning hinders subsequent recognition in children under 4 1/2 years. *Frontiers in Psychology, 11*. https://doi.org/10.3389/fpsyg.2020.00500

Nakamura, K., Kuo, W. J., Pegado, F., Cohen, L., Tzeng, O. J., & Dehaene, S. (2012). Universal brain systems for recognizing word shapes and handwriting gestures during reading.

Proceedings of the National Academy of Sciences of the United States of America, 109(50), 20762-20767. https://doi.org/10.1073/pnas.1217749109

Qiu, Y., & Zhou, X. (2010). Perceiving the writing sequence of Chinese characters: An ERP investigation. *NeuroImage, 50*(2), 782-795. https://doi.org/10.1016/j.neuroimage.2009.12.003

R Core Team. (2020). *R: A language and environment for statistical computing.* Vienna, Austria: R foundation for statistical computing. Retrieved from https://www.r-project.org/

Schubert, T., Reilhac, C., & McCloskey, M. (2018). Knowledge about writing influences reading: Dynamic visual information about letter production facilitates letter identification. *Cortex, 103*, 302-315. https://doi.org/10.1016/j.cortex.2018.03.020

Shen, H. (2004). Level of cognitive processing: Effects on character learning among non-native learners of Chinese as a foreign language. *Language and Education, 18*(2), 167-182. https://doi.org/10.1080/09500780408666873

State Language Commission. (2020). *Stroke Orders of The Commonly Used Standard Chinese Characters*. Beijing: The Commercial Press.

Tan, L. H., Spinks, J. A., Eden, G. F., Perfetti, C. A., & Siok, W. T. (2005). Reading depends on writing, in Chinese. *Proceedings of the National Academy of Sciences*, *102*(24), 8781-8785. https://doi.org/10.1073/pnas.0503523102

Tan, L. H., Xu, M., Chang, C. Q., & Siok, W. T. (2013). China’s language input system in the digital age affects children’s reading development. *Proceedings of the National Academy of Sciences*,*110*(3), 1119-1123. https://doi.org/10.1073/pnas.1213586110

Tsai, C. H., Kuo, C. H., Horng, W. B., & Chen, C. W. (2012). Effects on learning logographic character formation in computer-assisted handwriting instruction. *Language Learning and Technology, 16*(1), 110-130. http://dx.doi.org/10125/44277

Tseng, M. H., & Chow, S. (2000). Perceptual-motor function of school-age children with slow handwriting speed. *American Journal of Occupational Therapy, 54*(1), 83-88. https://doi.org/10.5014/ajot.54.1.83

Wong, Y. K., & Zhou, Y. (2022). Effects of metalinguistic awareness on Chinese as a second language spelling through the mediation of reading and copying. *Reading and Writing*, *35*(4), 853-875. https://doi.org/10.1007/s11145-021-10167-0

Xu, J. J., Jiang X. (2022). The relationship between stroke order and writing speed of Chinese second language learners. *Applied Linguistics*, (1), 70-80. 10.16499/j.cnki.1003-5397.2022.01.004

Xu, Y., Chang, L. Y., Zhang, J., & Perfetti, C. A. (2013). Reading, writing, and animation in character learning in Chinese as a foreign language. *Foreign Language Annals, 46*(3), 423-444. https://doi.org/10.1111/flan.12040

Xu, Z., Liu, D., & Joshi, R. M. (2020). The influence of sensory-motor components of handwriting on Chinese character learning in second-and fourth-grade Chinese children. *Journal of Educational Psychology, 112*(7), 1353-1366. https://psycnet.apa.org/doi/10.1037/edu0000443

Yang, Y., Zuo, Z. T., Tam, F., Graham, S. J., Tao, R., Wang, N. Z., & Bi, H. Y. (2019). Brain activation and functional connectivity during Chinese writing: An fMRI study. *Journal of Neurolinguistics, 51*, 199-211. https://doi.org/10.1016/j.jneuroling.2019.03.002

Yeung, P. S., Ho, C. S. H., Chan, D. W. O., & Chung, K. K. H. (2013). Modeling the relationships between cognitive-linguistic skills and writing in Chinese among elementary grades students. *Reading and Writing, 26*(7), 1195-1221. https://doi.org/10.1007/s11145-012-9411-

Yin, Y. L., & Zhang, Q. F. (2020). Chinese characters are read using not only visual but also writing motor information. *Psychophysiology, 58*(1), 1-19. https://doi.org/10.1111/psyp.13696

You, H. (2003) How is the acquisition of Chinese characters by learners from the non-Chinese character cultural sphere affected by stroke numbers component numbers and topological structural patterns. *Chinese Teaching in the World*, (2), 71-81.

Yu, H., Gong, L., Qiu, Y., & Zhou, X. (2011). Seeing Chinese characters in action: An fMRI study of the perception of writing sequences. *Brain and Language, 119*(2), 60-67. https://doi.org/10.1016/j.bandl.2010.11.007

Zhang, H. (2014). A review of stroke order in hanzi handwriting. *Language Learning in Higher Education, 4*(2), 423-440.

Zhu, Y., & Hong, W. (2005). Effects of digital voiced pronunciation and stroke sequence animation on character memorization of CFL learners. *Journal of the Chinese Language Teachers Association, 40*(3), 49-70.

Zhu, Y., Fung, A. S., & Wang, H. (2012). Memorization effects of pronunciation and stroke order animation in digital flashcards. *CALICO Journal, 29*(3), 563-577. https://www.jstor.org/stable/calicojournal.29.3.563